ABSTRACT

FITNET is a four-year European thematic network with the objective of developing and extending the use of fitness-for-service (FFS) procedures for welded and non-welded metallic structures throughout Europe. It is partly funded by the European Commission within the fifth framework program and it was launched in February 2002. The network currently consists of about 50 organisations from 17 European countries and supported by institutions from USA, Japan and Korea. Further information can be found in the FITNET TN website: http://www.eurofitnet.org. The FITNET FFS Procedure is built up in four major analysis modules namely fracture, fatigue, creep and corrosion. The first official draft is available in early 2006 in the form of an official CEN document. Industrial components are as a rule exposed to fluctuating loads and hence consideration of fatigue damages accumulation or of fatigue crack growth is a critical issue. The aim of this paper is to present the features and the main analysis routes of the FITNET FFE Fatigue Module of the FITNET FFS Procedure to assess the fatigue life of the load carrying metallic components manufactured with and without welds. The paper includes an industrial case from ship structure for the application of two fatigue assessment routes.

Keywords: Fitness-for-Service, Fatigue, Cyclic Loading, Defect Assessment, Welds, Engineering Structures

INTRODUCTION

FITNET is a European networking project designed to promote the development of a Fitness-for-Service (FFS) Procedure for assessing the structural integrity of metallic welded or non-welded structures transmitting loads. In particular it embodies techniques for dealing with defects known or postulated to be present in a structure together with the possible growth of such defects by a range of mechanisms and the assessment techniques required to evaluate failure risk. It is intended to provide an umbrella scheme into which results from EC-funded projects, national programmes and in-kind funded contributions from industry and academia are harnessed to the common goal of a fitness-for-service procedure based on European advanced technology. The FITNET FSS procedure aims to provide methodologies for the assessment of fatigue damage in components, which may affect its fitness for service.

It is aimed to develop FFS Procedure to satisfy the following basic requirements:

- Be an advanced, fully validated method for determining the fitness for service of various structures or components manufactured from metallic materials, with and without welding.
- To cover four major failure modes of engineering structures, namely: fracture, fatigue, creep and corrosion damage and all aspects essential for advanced design in all industrial sectors.
- To be readily usable by general industry and make a major contribution to cost saving, particularly for small and less technically advanced companies, whilst still improving structural safety.

To support these objectives, The FITNET Thematic Network with its wide range of expertise and the activities of its member organisations embraces results
obtained in numbers of completed EU Projects such as INTEGRITY, PLAN, WAFS and JOTSUP, etc. It also covers the recent developments in other on-going EC funded projects, networks and advances in national and industrial codes such as BS7910, R5&R6 and AP1 579. structure as given in Fig. 1

Although several fitness-for-service procedures already exist (e.g. BS7910, API579, R6 and SINTAP) [1,4-8], they tend to be aimed at a particular industrial sector, or a single failure mode (e.g. SINTAP covers only fracture), or they are national documents. There is therefore a need for a single and agreed European FFS Procedure, which could ultimately become a European (CEN) standard for assessing the flaws (such as cracks, welding defects and corrosion damage) in welded and non-welded metallic load-carrying structures operating under various loading conditions.

A European-wide FITNET-FFS procedure is essential to regulators, especially as they are now faced with an increase in multi-national owners and operators of industrial systems. By the same token, industries will benefit from having at their disposal a tool for cross-regional benchmarking. This should also provide increased flexibility in the selection of suppliers, the option to work to the same basis and the re-used of calculations/solutions for similar components. The FITNET FFS Procedure is currently under development is structured in four major assessment modules, to assess the postulated flaw (at the design and fabrication stages of a new component) or real flaw(s) detected during in-service inspection. The present work aims to present the current state of the FITNET FFS Fatigue Module and describe its major features and assessment routes.
FITNET FSS PROCEDURE - FATIGUE MODULE

The FITNET-FFS procedure with its easy-to-use features and similarly-structured four assessment modules is consistent with current FFS procedures. A special effort has been made to develop procedures for each module (similar to the SINTAP procedure) which enable the assessment of both conventional and advanced (e.g. laser beam, friction stir etc.) structural welds.

In order to develop four assessment modules, the FITNET Thematic Network is based on four respective working groups (WG):

- WG1: Fracture
- WG2: Fatigue
- WG3: Creep
- WG4: Corrosion

Each WG is working on the implementation of currently available and technically sound international procedures as well as technical items which need to be improved, added or validated for the European Fitness for Service (FFS) procedure, with the overall structure as given figure. 1.

BACKGROUND INFORMATION ON FATIGUE MODULE DEVELOPMENT

The FITNET fatigue module will draw on existing procedures, notably fatigue design rules and recommendations (e.g. IIW, Eurocode) and flaw assessment procedures (e.g. BS 7910, API 579, R6). Noting that many of these were developed for a specific manufacturing technology, a single industrial sector or as a national document, the aim will be to extract relevant information for presentation as a general procedure that addresses the needs of a wide range of industries. In this respect, the industries represented by the WG membership is suitably diverse, including offshore, shipbuilding, bridges, pressure vessels, chemical, earth moving, automotive, railway, nuclear, mechanical industry & SMEs. It is anticipated that the procedures will embody the following:

+ The development of coherent, multidisciplinary and easy to use fatigue assessment routes based on representative and significant existing documents;
+ The implementation of advanced fatigue databases (covering various materials); and new manufacturing or assembly processes (laser, laser-hybrid, friction stir welding);
+ The development of a “multi-scale mechanical approach” by providing conventional and multiaxial fatigue criteria (semi-local and local mechanical approach) for either constant or variable amplitude loading conditions.
+ The development of specific guidelines on conventional and advanced fatigue design methods for welded assemblies (S-N curves, structural stress) and non-welded assemblies;
+ The establishment of a practical Non-Destructive Technology recommendation (capability, accuracy; reliability) for defect size assessment;
+ The implementation of dedicated databases which will be the input for other WG Modules (such as a “Compendium of Residual Stresses”) in order to have a rational link with the global FFS procedure.

THE FATIGUE MODULE AND ASSESSMENT ROUTES

The FITNET fatigue module provides a series of assessment procedures or routes for evaluating the effect of cyclic or fluctuating loads. Two basic scenarios are foreseen:

- a) There is no identified pre-existing flaw or defect, and the goal of the analysis is to determine the accumulation of fatigue damage at a critical location (fatigue damage analysis). In this case the basic approach is to determine the fluctuating stress range at the location in question and relate this to appropriate fatigue life curves. Three different routes are proposed (Routes 1, 2 and 3), depending on the complexity of the loading.
- b) A real or postulated defect or flaw is present (routes 4 and 5), and the goal of the analysis is to determine:
  - for volumic flows, the reduction of the fatigue resistance as defined in route 1;
  - for planar, cracklike or crack, the growth of that flaw to a certain critical size (fatigue crack growth analysis – Route 4)

Both option a) and b) can be applied to either welded or non-welded structures. It is noted that for a given component, both aspects may need to be considered in cases for which the location of a reported defect does not coincide with that of highest loading. The overall scheme is shown in Fig. 2.

Route 1 – Fatigue damage assessment using nominal stresses

This route considers nominal elastic stress values for the location of interest and the fatigue life $N_f$ is determined from a set of S-N curves classified according to different classes or levels of fatigue resistance i.e. the effects of local geometric, weld or microstructural details and, if relevant, residual stresses are accounted for in the S-N curve itself. It is based on currently used procedures (e.g. IIW (ref [1]) for welded joints. The linear cumulative damage law is used to deal with variable load spectra:

$$\frac{N_f}{N_{f1}} + \frac{N_f}{N_{f2}} + \frac{N_f}{N_{f3}} + \ldots \leq 1$$

where D is a scalar measure of the allowable damage at the end of the required life (commonly D=1 but it can also be set to a value less than one)
Route 2 – Fatigue damage assessment using either structural stress or notch stress, coupled with appropriate S-N curves

This route considers that the appropriate structural stress in a critical area of a component could be calculated by FEA or by formula. In some case it could also be measured by following specific methods. Two approaches are possible:

a) calculate the structural stress and apply with appropriate class S-N curves;

b) calculate a notch stress via stress concentration factors such as $K_t$ or $K_f$, and apply with appropriate S-N curves, ref [2,3].

Route 3 - Fatigue damage assessment considering elastic-plastic material behaviour at critical features and strain-range based fatigue life curves

This route is mainly directed at non-welded applications and foresees direct calculation of strains at a critical location using an appropriate elastic or elasto-plastic description of the material behaviour. The fatigue life is then determined from a strain range vs. cycles relation such as the Manson-Coffin law, for which the implicit failure criterion is related to crack initiation. It is also noted that the analysis can be taken further by considering subsequent crack growth using fracture mechanics (route 4). These analyses can be performed cycle-by-cycle, allowing for non-linear damage accumulation effects if necessary.

Route 4 – fatigue crack propagation

This route addresses the assessment of detected or postulated planar flaws that can be considered as macro-cracks (i.e. with dimensions typically greater than millimetres). The initial flaw position, size and orientation can be determined in two ways:

a) Based on the reported or detected size from non-destructive inspection results;

b) Postulated defect, based on consideration of service experience, the manufacturing process, resolution limits of a NDE technique, from the threshold stress intensity factor etc. Recommendations are given for assessing flaws in plain, unwelded material and for those associated with welds.
a. Flaws in unwelded material:
The selected baseline fatigue crack growth equation is that originally proposed by Forman and Mettu and subsequently used in the NASGRO software for non-welded application. It accounts for the stress intensity factor range, the mean stress level and other important parameters and is considered a suitable universal formula for fatigue crack growth (FCG) analysis. It has the form:

$$\frac{da}{dN} = C \left[ \left( \frac{1-f}{1-R} \right)^2 \right]^n \left( 1 - \frac{\Delta K_{th}}{\Delta K} \right)^p \left( 1 - \frac{K_{max}}{K_c} \right)^q$$

(2)

where $C$, $n$, $p$, and $q$ are material constants, $f$ is the ratio of opening and maximum $K_{max}$ stress intensity factors, $R$ is stress ratio, $K_c$ is the critical stress intensity factor, and $\Delta K_{th}$ is the threshold stress intensity factor range.

b. Flaws in either welded or unwelded material
For the assessment of flaws associated with welds or for assessing flaws in unwelded material for cases where the Forman and Mettu parameters are not available, use is made of the Forman and Mettu expression reduced to the standard Paris Law form:

$$\frac{da}{dN} = C.\Delta K^m$$

(3)

where $A$ and $m$ are constants that depend on the material, environment and the applied conditions, including any that are specifically relevant to flaws in welds, notably the presence of residual stress.

If it can be shown that $\Delta K$ is below an appropriately determined threshold value, the crack growth rate may be deemed negligible. These expressions can be integrated to provide estimates of crack growth over a fixed number of cycles or for the number of cycles required to reach a critical crack size, determined using the FITNET fracture assessment module. The acceptability of the real or postulated flaw can then be determined in relation to the required cyclic life. For the $K$ solutions themselves, the user will have access to a special compendium common to all the FITNET modules.

Route 5 – Non-planar flaw assessment

Non-planar flaws can be assessed in the same way as planar flaws using route 4. Since they are not crack-like, this will be conservative. However, it may be the only option if it is necessary to quantify the growth of the flaw under fatigue loading and to ensure the margin against unstable fracture at a specific crack size. Otherwise, Route 1 using S-N curves for welded joints can be applied directly, in cases for which the equivalent fatigue strength are established for the non-planar flaw under consideration. At present, this approach is only available for assessing slag inclusions or porosity in steel or aluminium alloy butt welds.
Fig. 3 Detailed flow chart of the five FITNET fatigue assessment routes

ALTERNATIVE AND SPECIFIC ASSESSMENTS

Alternative approaches and specific assessments in fatigue are also included in the FITNET procedure. The objective is to identify limits between the modules in the overall FITNET procedure for complex service conditions and also to consider "emergent" industrial approaches to assess fatigue life under specific conditions. The areas covered by this part are focused on:

+ Equivalent constant amplitude stress
+ Stress intensity approach
+ Multi-axial fatigue assessment
+ Contact and fretting fatigue
+ Fatigue - creep interactions
+ Fatigue - corrosion interactions

VI - APPLICATION EXAMPLES (ROUTES 1 & 2)

The application of FITNET fatigue assessment procedure is illustrated via a case of study.

1 - Presentation of the Shipbuilding Industry Case study:

This example illustrates the fatigue assessment routes used by the shipbuilding industry during the design phase. In particular, a scallop in a longitudinal stiffener of the deck of a tanker is considered.

The ship has the following dimensions:

Length \( L = 300 \text{ m} \)

Breadth \( B = 57 \text{ m} \)

Depth \( D = 30 \text{ m} \)

Draught \( d = 21 \text{ m} \)

Block coefficient \( C_b = 0.85 \) (ratio of the loaded ship mass to 1.025 LBT)
Figure 4 presents the cross section of the overall design of the ship structure. Figure 5 presents the structural class of weld detail under study.

The structure scantling (dimensions) fulfil the classification rules which means that the midship modulus is equal to:

\[ W_m = F L^2 B (C_b + 0.7) \times 10^{-6} \text{ in } m^3 \]

**Loading conditions**

The maximum midship wave bending moments are:

- **Hogging:**
  \[ M_{wH} = 190 F L^2 B C_b 10^{-3} \text{ (in kN.m)} \]  \( (5) \)

- **Sagging:**
  \[ M_{wS} = 110 F L^2 B (C_b + 0.7) 10^{-3} \text{ (in kN.m)} \]  \( (6) \)

From the ship rules, the long-term wave bending moment distribution for 25 years life can be represented in terms of stresses and number of associated cycles as given in Table 1.

<table>
<thead>
<tr>
<th>( \Delta S/S_{max} )</th>
<th>( n_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
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<tr>
<td>0.88</td>
<td>68</td>
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<tr>
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<td>68 421 055</td>
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<td>( \Sigma )</td>
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Table 1 Long-term wave bending moment distribution for a 25 year period.
2 - Analysis

This industrial example directly involve routes 1 and route 2 of the FITNET fatigue module, ref [4. The objective is to evaluate the accuracy of the results which could be provided by each route.

Fatigue damage analysis using Route 1 (nominal stress approach)

Input parameters

Route 1 uses the nominal stress, i.e., the longitudinal stress range in deck induced by the wave bending moment. In that case the bending moment range is:

\[ \Delta M = M_{w,S} + M_{w,H} (7) \]

\[ \Delta M = FL^2 B \times 10^{-3} \left[ 190C_b + 110(C_b + 0.7) \right] \text{ (in kN.m)} (8) \]

Then the associated maximum stress range is:

\[ \Delta S = \frac{\Delta M}{W} \]

\[ \Delta S = \frac{190C_b + 110(C_b + 0.7)}{C_b + 0.7} \times 10^{-3} = 214 \text{ MPa} \]

The S-N curve can be found in the extract from the FITNET classification scheme in Table 2.

| Welded Joint Classification (cont’d) |
| Joint Classification | Description | Examples |
| Category 6 E F | 2) Intermittent fillet welds | |
| | 3) As (2) but adjacent to cutouts. | |

Table 2

Therefore the S-N curve is the F curve whose characteristics are:

\[ m = 3 \quad K_{D1} = 1.726 \times 10^{12} \quad \text{Stdv} = 0.2183 \quad (11) \]

The design curve has 2 slopes curve without a cut-off at minus 2 standard deviations.

The change of m=3 slope fixed at 10^7 cycles:

\[ K_{D1} = 6.316 \times 10^{11} \]

The slope change stress range is:

\[ \Delta S_l = 39.8 \text{ MPa} \]

then the equation for the second part of the S-N curve is:

\[ m = 5 \quad K_{D2} = \Delta S_l^5 \times 10^7 = 9.987 \times 10^{14} \quad (12) \]

Results of the calculation (Route 1)

Based on the stress distribution in Table 1 and the above S-N reference curve, the cumulative fatigue damage based on Miner’s rule can be calculated ( see Table 3). The resulting total damage calculation for this structure was D = 0.61, which is < 1. Thus, according to Miner’s rule the structure is safe.

Fatigue damage analysis using Route 2 (notch stress approach)

Input parameters

The second option is to assess the fatigue damage using FITNET Route 2, by using the notch stress range approach. The appropriate equation is given to calculate the notch stress using the nominal stress, the local hot-spot stress concentration factor and the notch effect factor. In the present example, the local hot-spot stress concentration factor \( K_g \) was determined by finite element analysis of the detail in tension to be 1.1

The FITNET procedure provides the following notch factor:

\[ K_f = \frac{l(q/30)^{1/2}}{3} \]

and the following values:

| Joint Classification | Description | Examples |
| Category 6 E F | 2) Intermittent fillet welds | |
| | 3) As (2) but adjacent to cutouts. | |

Then

\[ K_f = 2.90 \]

The rules book S-N curve to be associated to the notch stress is the following curve:

\[ m = 3 \quad K_{D1} = 1.692 \times 10^{13} \quad (13) \]

The slope change stress range is:

\[ \Delta S_l = (K_g / 10^5)^{1/3} = 119 \text{ MPa} \]

and the second part of the S-N curve is:

\[ m = 5 \quad K_{D2} = 2.386 \times 10^{17} \quad (14) \]

Results of the calculation (Route 2)

Working as before, the Miner’s rule sums and total summation are included in Table 3. The total damage calculation using this route is D = 0.52, which is again < 1, indicating that the structure is safe.
Table 3

<table>
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<tr>
<th>$\Delta S / S_{\text{max}}$</th>
<th>$\Delta S_{\text{nom}}$</th>
<th>$\Delta S_{\text{notch}}$</th>
<th>$n_i$</th>
<th>$n_i / N_{i\text{nom}}$</th>
<th>$n_i / N_{i\text{notch}}$</th>
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</table>

where:

italic $\Rightarrow m = 5$

$N_i = K_{D1} / \Delta S^3$ or $N_i = K_{D2} / \Delta S^5$; $K_{D1}$ and $K_{D2}$ being the constants of the design S-N curves for the two stages with slopes of 3 and 5 respectively; $D = \Sigma n_i / N_i$

**Synthesis**

The example illustrated the fatigue assessment routes used by the shipbuilding industry during the design phase by considering the example of a scallop in a longitudinal stiffener of a tanker ship deck.

Route 1 and 2 of FITNET Fatigue module were used to calculate fatigue damage of this structural detail. By using both of these applications, the results of this analysis indicated safe service condition. The fatigue damage calculated by using Route 2, which incorporates more accurate input parameters (FEA), provides a damage factor $D = 0.52$, which is 17% less than that from route 1.

**CONCLUSION**

FITNET is a four-year European thematic network with the objective of developing and extending the use of fitness-for-service procedures for welded and non-welded metallic structures throughout Europe.

The FITNET-FFS procedure, currently under development and validation, has four major modules namely: Fracture, Fatigue, Creep and Corrosion. It is aimed to have similarly structured modules overall coherences with to currently-used procedures and the added feature of using an easy to use procedure. Special effort has been made to develop welding sections for each module (similar to the SINTAP procedure) to treat the conventional and advanced (e.g laser beam, friction stir etc.) structural welds.

This paper presented the overall FITNET FSS Fatigue Module and provided an overview of the main routes which are currently under development to assess the fatigue life of the welded and non-welded metallic structures. Special effort has been made to include approaches for welded sections and to treat conventional and advanced (e.g laser beam, friction stir etc.) structural welds.

By providing a range of assessment routes, the module aims to cover the needs of analysts which can vary according to the basic fatigue resistance data available (S-N curves or fatigue crack growth laws) and the level of knowledge of local stress distributions (nominal, structural or notch stresses). Further, it exploits the global framework of the FITNET procedure to provide access to K solutions, basic materials properties, residual stress distributions, guidance on NDE, etc.
An industrial application illustrated the fatigue assessment routes, with the example taken from the shipbuilding industry. Routes 1 (nominal stress) and 2 (local notch stress) of the FITNET fatigue module were used to calculate fatigue damage. Both indicated that the design was safe but route 2, with the local notch stress derived by FEA, proved to be the less conservative of the two with 17% less damage.

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References